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Validation Test Report for the Coastal Wave Refraction and Diffraction Model

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13. ABSTRACT *(Maximum 200 words)*

In coastal water, wave propagation is affected by many dynamic processes, including shoaling, refraction, diffraction, and energy dissipation. The existing RCPWAVE wave model in the Navy-Standard surf model was developed for open coast with slowly varying bathymetry. It cannot handle certain coastline configurations such as those that include islands and peninsulas. It also has a serious numerical instability problem. The more recently developed REF/DIF1 wave model has a more robust formulation and does not suffer from the same limitations. In this report, a systematic set of tests was conducted to evaluate the REF/DIF1. The tests evaluate the shoaling and refraction, combined refraction and diffraction, energy dissipation, and wave-current interaction properties of the model. The model results were compared to analytic solutions from linear wave theory, laboratory and field data. REF/DIF1 was found to perform adequately in all tests. The REF/DIF1 has been integrated into the Navy-Standard surf model.

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VALIDATION TEST REPORT FOR THE COASTAL WAVE REFRACTION AND DIFFRACTION MODEL

I. INTRODUCTION

Wave modeling provides essential information for many Army and Navy operations. Many other numerical models, such as surf, water clarity, acoustic, and radar backscatter models all require wave data or estimates as input conditions. In shallow water, wave propagation is affected by many dynamic processes, including shoaling, refraction, diffraction, and energy dissipation due to bottom friction and depth-induced breaking. The coastal wave model (REF/DIF1) has been developed to model these processes (Kirby and Dalrymple 1994). Although there are other coastal wave models such as SWAN (Simulation Waves Nearshore) (Ris et al. 1994) in existence and undergoing continuing development, REF/DIF1 is considered to be the most complete for combined refraction and diffraction computation.

In the present Tactical Environmental Support System (TESS) surf model, the Regional Coastal Process Wave Propagation wave model (RCPWAVE) (Ebersole 1986) was implemented for refraction and diffraction computation. However, the numerical schemes used in RCPWAVE were developed only for open coasts with slowly varying bathymetry. In some cases, the bathymetry needs to be smoothed to achieve numerical stability. In addition, it cannot be used for locations with a complex bathymetry, such as islands or semienclosed coastal areas. REF/DIF1 is now being implemented in the TESS surf model to eliminate those limitations.

The REF/DIF1 model solves the mild slope equation with the parabolic approximation. The model is solved in finite difference form using an efficient implicit scheme. Detailed formulas and explanations are documented in the REF/DIF1 manual and are, therefore, not repeated here. The model also includes the computation of wave-current interaction that is important at areas near inlets and straits. A complementary wave model, REF/DIF-S (Kirby and Ozkan 1994), has also been developed. It contains all of the features of REF/DIF1, but additionally allows propagation of a spectrum of waves. It is effectively the same as running REF/DIF1 for many ocean waves except that it propagates all of the waves simultaneously. Consequently, it gives a more accurate prediction of the heights and locations of depth-induced breakers in the surf zone. Both REF/DIF1 and REF/DIF-S are being validated using the Duck Experiment on Low-frequency and Incident-hand Longshore and Across-shore Hydrodynamics (DELILAH) field study data set.

Although some examples were included in the original REF/DIF1 manual, no systematic testing was presented. In this report, all stated modeling processes in REF/DIF1 are tested against either analytic solutions or laboratory and field results.

II. VALIDATION TESTS

A. Shoaling and Refraction Test

1. Analytic Solution

The wave height in shallow water, H, is related to the deep-water wave height, H_0, by the following expression

$$H = K_s \, K_r \, H_0 \,, \tag{1}$$

where K_s is the shoaling coefficient and K_r is the refraction coefficient. From linear theory (e.g., Dean and Dalrymple 1991), K_s and K_r are expressed as

$$K_s = \sqrt{C_{g0} / C_g} \tag{2}$$

$$K_r = \sqrt{\cos \theta_0 / \cos \theta} \,, \tag{3}$$

where C_g is the group velocity, θ is the wave angle, and the subscript 0 indicates deep-water conditions. The angle θ is related to the deep-water angle, θ_0, by Snell's law

$$\sin \, \theta = (\tanh \, kh) \, \sin \, (\theta_0) \,, \tag{4}$$

where h is the water depth and k is the wavenumber. The shoaling term K_s can be further derived as

$$K_s = \sqrt{1 \Big/ \left(1 + {2kh}/{\sinh 2kh}\right) \tanh k h} \;. \tag{5}$$

2. Model Setup and Results

The refraction and shoaling characteristics of the model were tested by comparing model results to that of linear theory. The test bathymetry consisted of a plane sloping beach with an offshore depth of 7 m and a slope of 0.009. Three different wave periods were used: $T = 3$ s, 10 s, and 17 s. This spanned the range from the deep-water limit ($h/L = 0.5$) to the shallow-water limit ($h/L = 0.05$), where L is the wavelength.

Other modeling parameters:

Domain: 720 m × 720 m
Grid spacing: 3 m × 3 m
At boundary: x = 0, $H = 1$ m

Because it is a parabolic model, REF/DIF1 has a limit on the incident angle of the wave with respect to the x axis, beyond which the results become suspect. Kirby (1986b) discusses the theoretical aspects behind the small-angle assumption of the parabolic approximation. For the majority of parabolic models, this limit can be taken to be approximately ±15° (Chen and Liu 1995). REF/DIF1, however, has a large-angle correction built into it. This feature contains the

Pade-approximated higher-order correction obtained by Booij (1981) and analyzed by Kirby (1986a). According to Kirby and Dalrymple (1994), REF/DIF1 should be able to accurately propagate obliquely incident waves up to ±70° approach angle. Four different wave angles were used for each wave period: 15°, 30°, 45°, and 60°.

Figures 1–12 show the comparisons of predicted wave heights and wave angles from the model to that from linear theory. It is clear that as the angles increase, the errors between model and theory increase. (The sudden decrease in wave height in the model results is associated with wave breaking, which the linear theory did not have.) However, the following behaviors were also noted:

- The short wave ($T = 3$ s) seemed to be more susceptible to increase in error with increase in angle than the long wave ($T = 17$ s). This is true when looking at the 30° approach angle cases for wave height. This may be due to the fact that as the angle increases, resolution in the y direction becomes more of a factor since the model is initialized by projecting the incident wave on the y axis at the offshore row. The resolution in the y direction (the *nd* parameter in the input file) may not have been sufficient to adequately discretize this projection for the shorter waves. The code is being modified to make y axis grid size equal to x axis grid size as an option at each forward step. This should eliminate many of the problems associated with poor longshore resolution.
- As the incidence angles increase, it is often the wave angle that deviates from linear theory first, rather than the wave height. Wave angle is not explicitly propagated through the model, but is calculated from the resultant complex amplitudes via the gradient of the phase function. This involves another discretization with its own properties of convergence, etc., that needs to be performed in addition to the approximation of the governing mild slope equation within this parabolic model. The accumulated error may explain this trend. The irregular wave version of

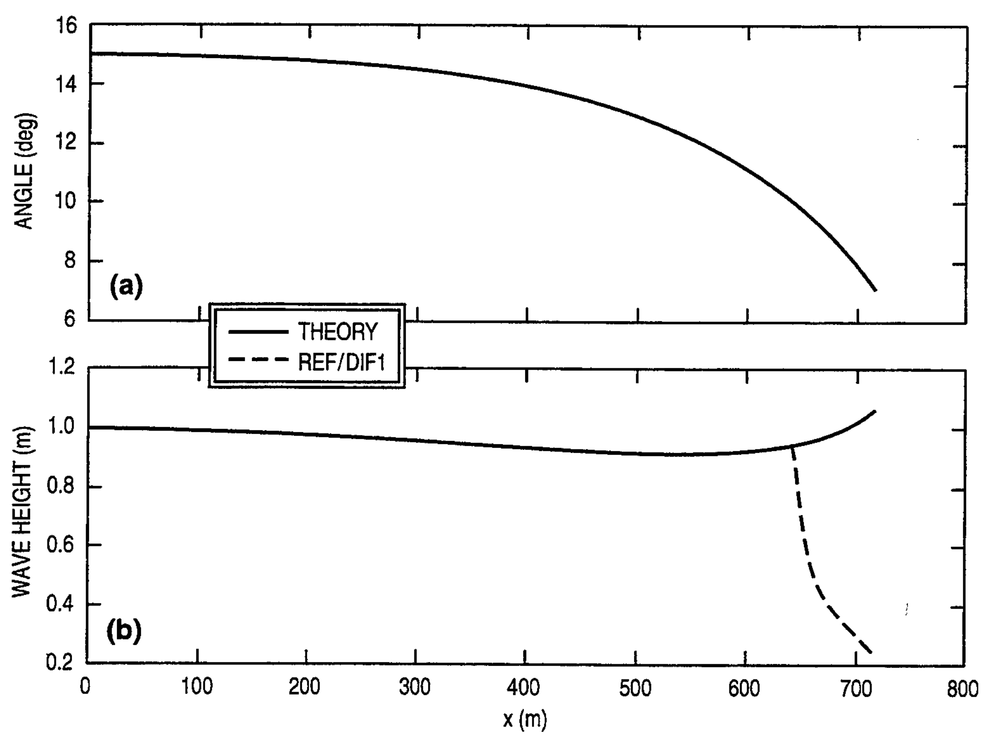

Fig. 1 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 3 s, angle = 15°.

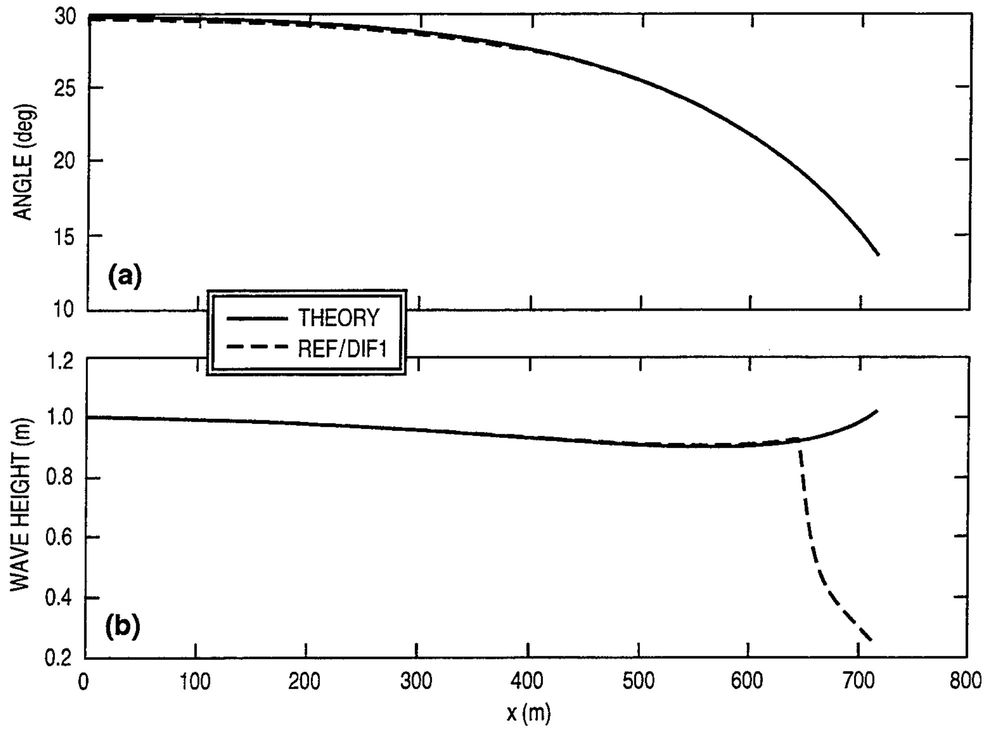

Fig. 2 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 3 s, angle = 30°.

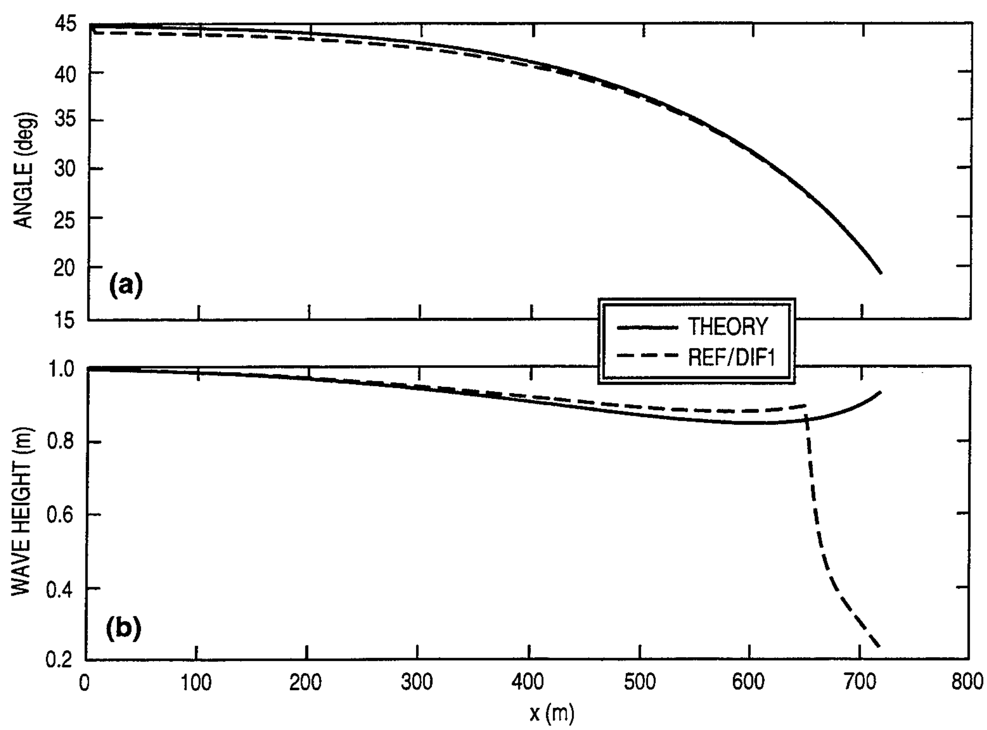

Fig. 3 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 3 s, angle = 45°.

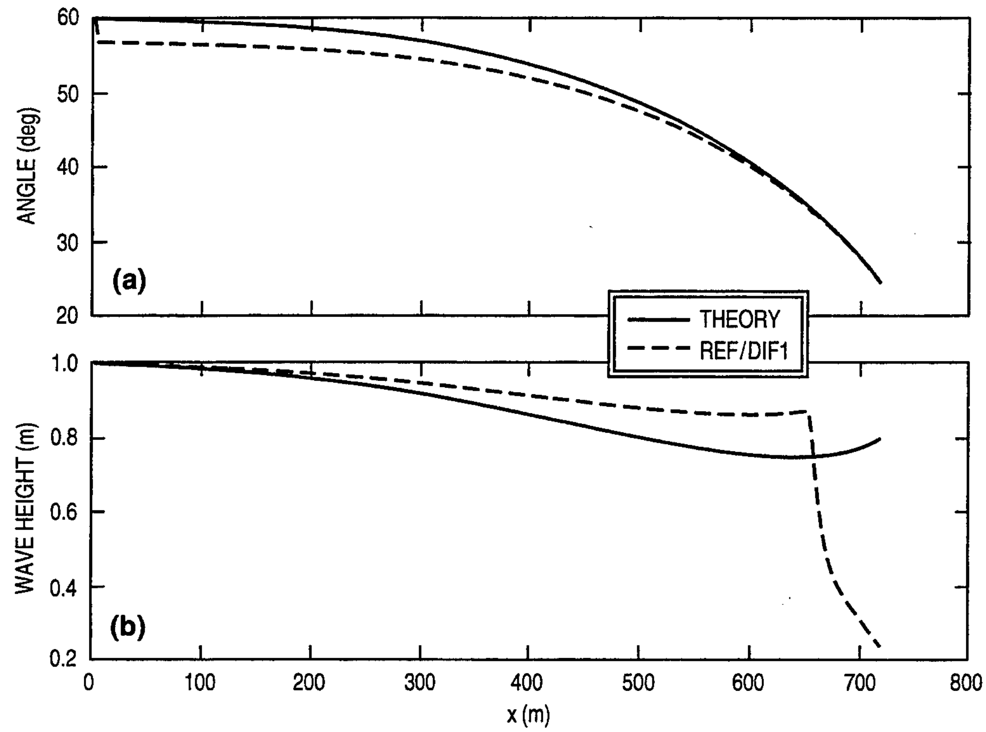

Fig. 4 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 3 s, angle = 60°.

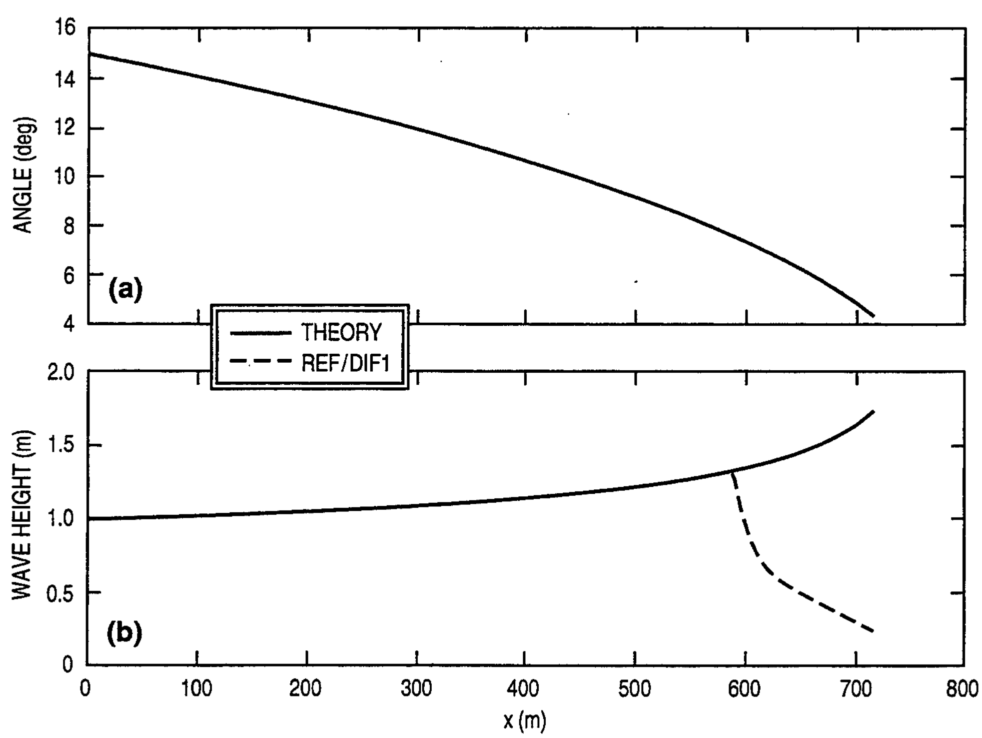

Fig. 5 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 10 s, angle = 15°.

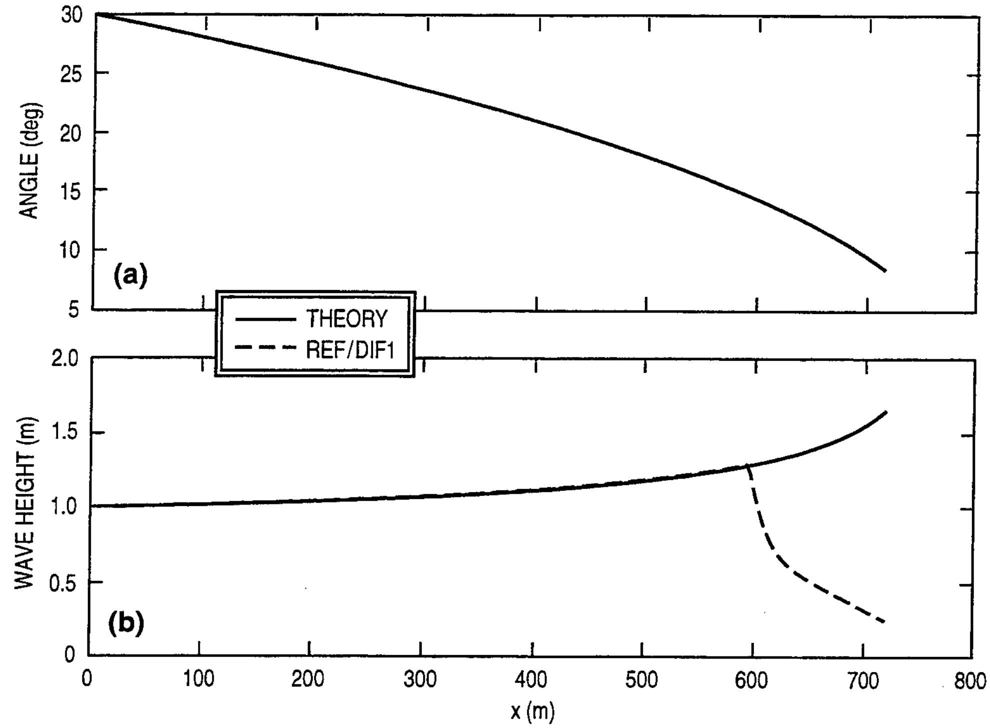

Fig. 6 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 10 s, angle = 30°.

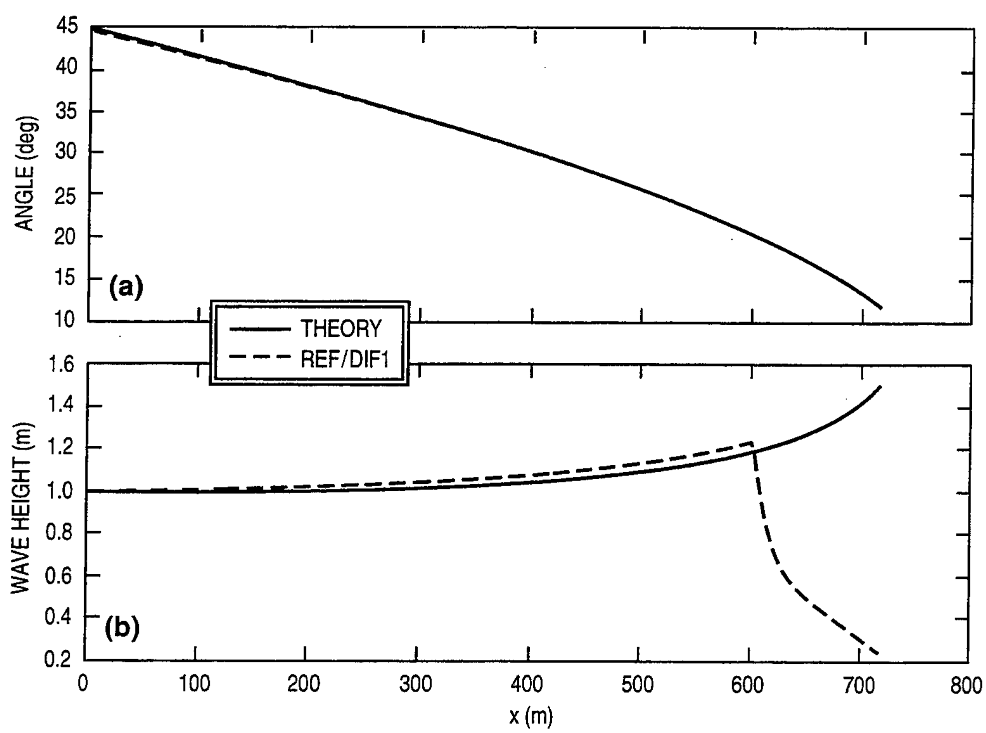

Fig. 7 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 10 s, angle = 45°.

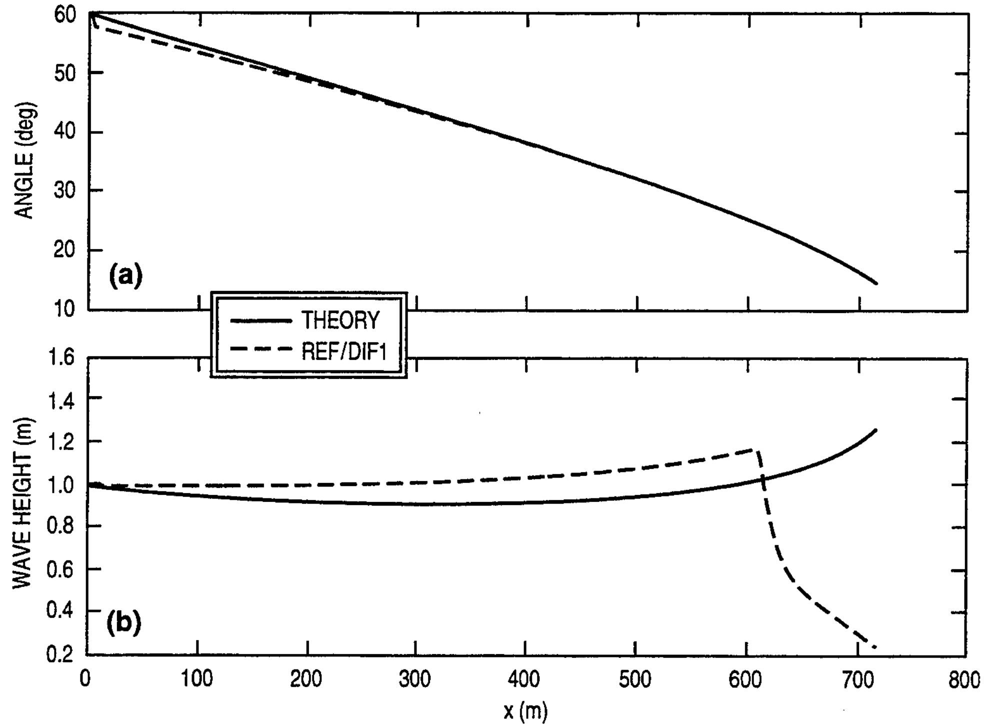

Fig. 8 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 10 s, angle = 60°.

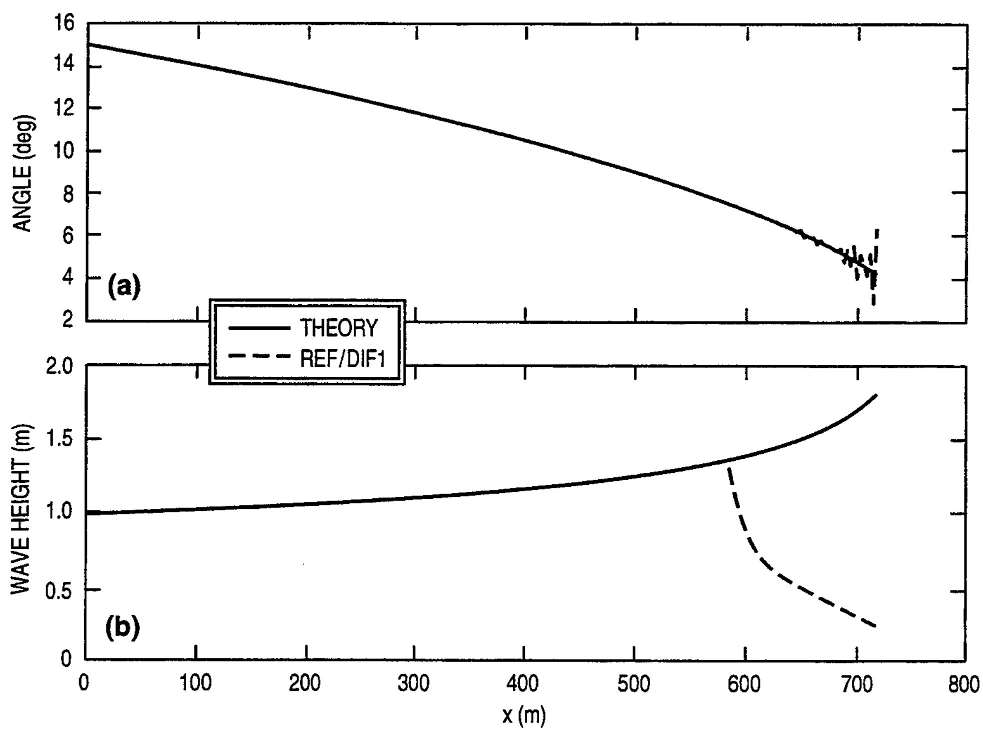

Fig. 9 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 17 s, angle = 15°.

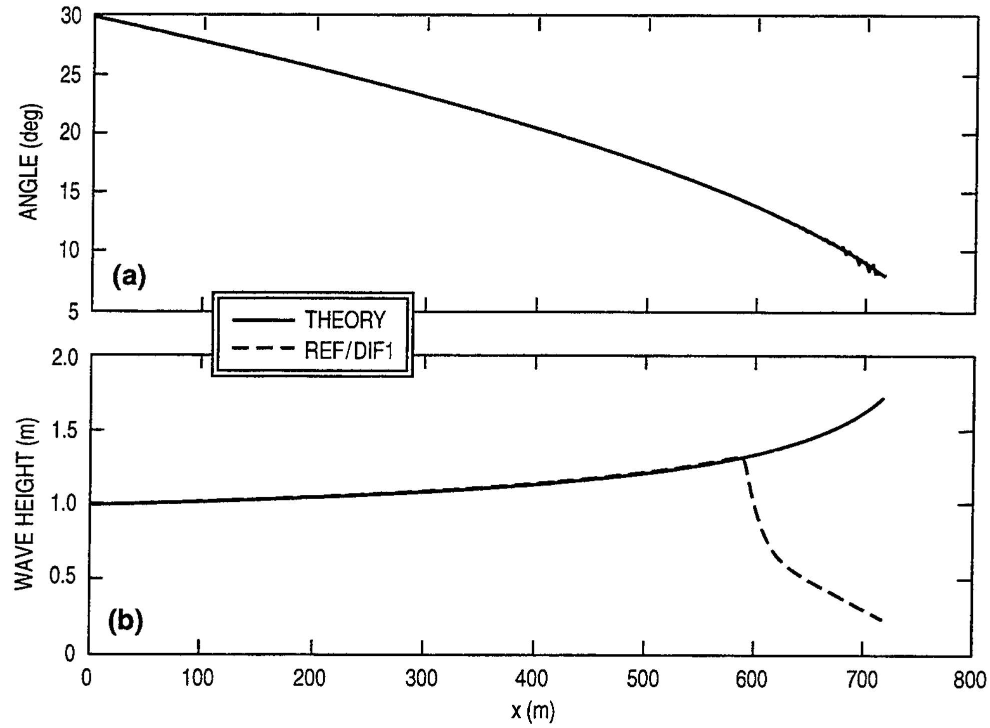

Fig. 10 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 17 s, angle = 30°.

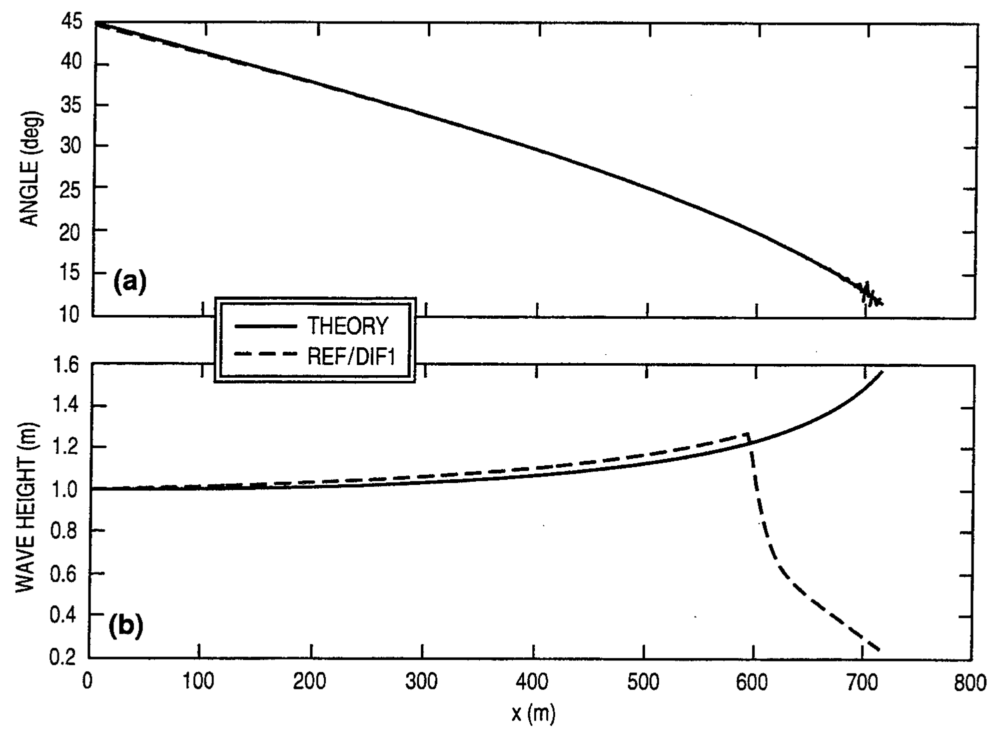

Fig. 11 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 17 s, angle = 45°.

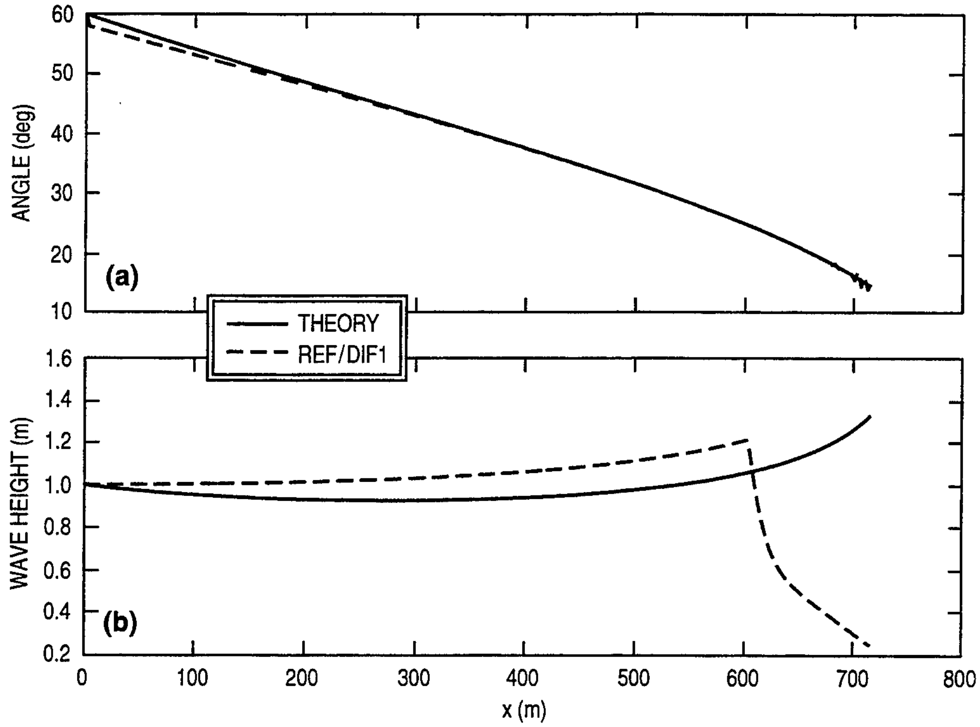

Fig. 12 — Comparison between model results and linear theory for refraction/shoaling test, (a) wave angle comparison and (b) wave height comparison. Wave period = 17 s, angle = 60°.

REF/DIF1, (REF/DIF-S) has a revised version of the subroutine used to calculate wave angle that apparently removes an undesired directional bias in the calculation (Chawla, pers. comm.). This may improve the angle calculation; however, this subroutine has not been added to REF/DIF1.

- It is clear that the results for approach angles of 60° might be considered marginal for many applications. This is most plainly seen in the 60° angle simulation for the $T = 17$ s case. While the model can reproduce the reduction in wave height due to shoaling from fairly deep water (see the $T = 3$ s case for 15° and 30° approach angles), it seems incapable of replicating the wave height attenuation due primarily to refraction at oblique angles. For the $T = 17$ s, 60° angle case, the model results for wave height do not reduce at all, while there is a clear reduction in wave height to some minima in the linear theory predictions.

As a result of these tests, it may be best to set an upper limit of ±40° for simulations using the REF/DIF1 model. This limit of 40° is a significant improvement over the ±15° value for lowest-order parabolic modeling. If angles larger than ±40° need to be run, the user should rotate the computational grid so that its x direction is closer to the wave approach angle.

B. Combined Refraction and Diffraction

1. Berkhoff-Booij-Radder (BBR) Shoal Experiment

a. Description of the Experiment

A set of laboratory wave experiments was conducted by Berkhoff et al. (1982). The experiments studied the focusing of a plane wave over a submerged elliptic shoal resting on a plane beach. The bottom contours and computational domain are illustrated in Fig. 13. The dashed lines,

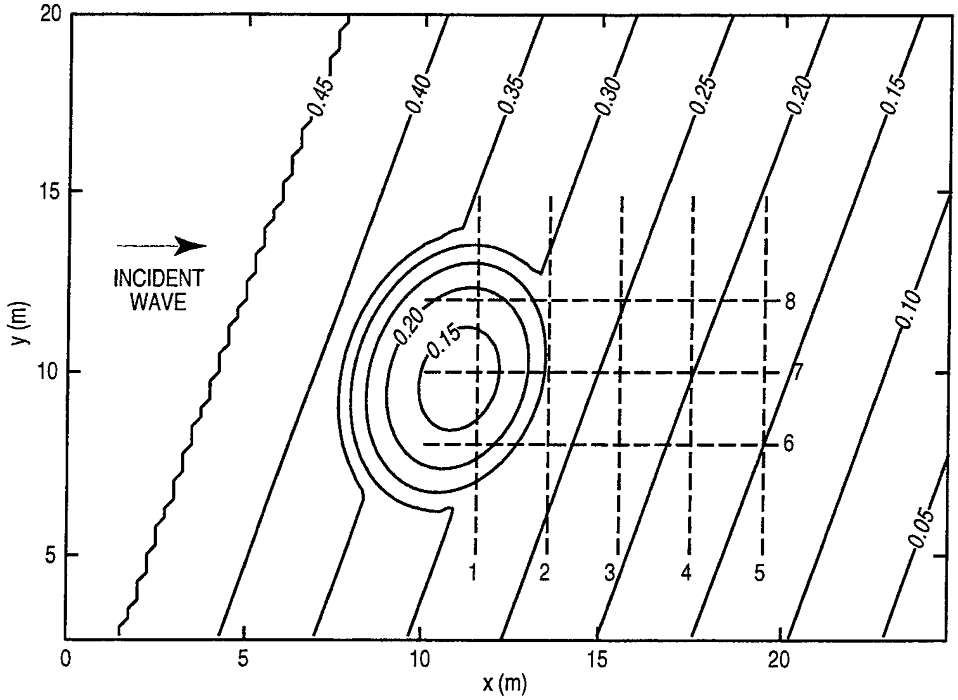

Fig. 13 — Bottom contours (in meters) and computational domains for the BBR shoal experiment

i.e. transects 1–8, indicate where the wave height distributions were measured. This test case provides a good test of the accuracy of the large angle and composite nonlinearity formulations used in REF/DIF1.

b. Model Setup and Results

The model was run with both linear and hybrid nonlinear dispersion relationships. The nonlinear Stokes-Hedges formulation is described in Kirby and Dalrymple (1986b).

Other modeling parameters:

Domain: 30 m $\times$ 30 m
Grid spacing: 0.25 m $\times$ 0.25 m
At boundary: x = 0, $H = 1$ m
Wave period = 1 s
Wave angle = 0°

In Fig. 14, a snapshot of the surface elevation is plotted. The diffraction fringes and phase jumps present in the photographs of the experiment are well captured. Wave height contours, normalized by the initial wave height, are plotted in Fig. 15. In Figs. 16–19, the wave height distribution at different transects are compared in detail. The solid and dashed lines represent model results with linear and nonlinear Stokes-Hedges dispersion, respectively. In general, nonlinear results match better with the measured data than those results from linear dispersion. The agreement between REF/DIF1 and experimental results is excellent.

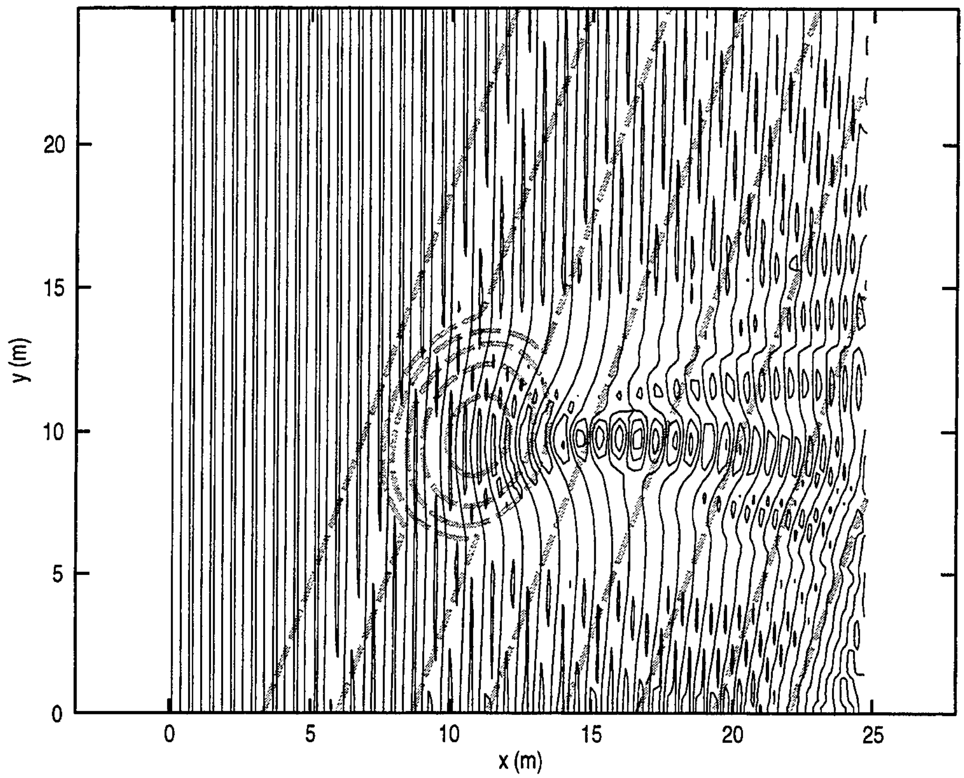

Fig. 14 — Instantaneous wave pattern: surface elevation contours, weakly nonlinear, BBR experiment

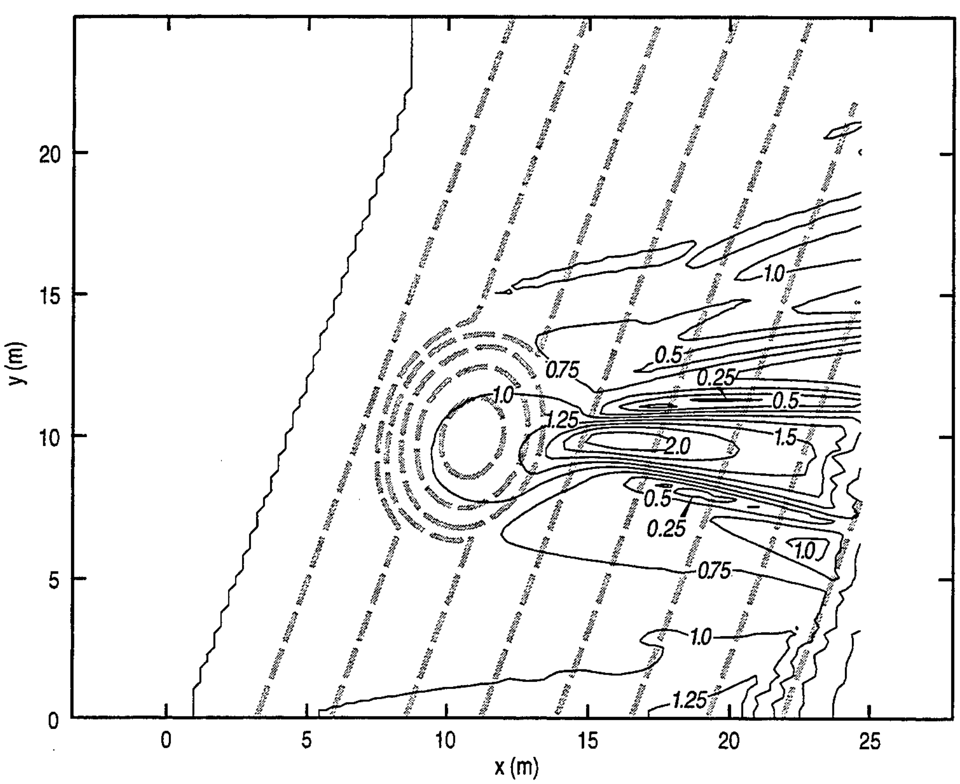

Fig. 15 — Wave height contours, weakly nonlinear, BBR experiment

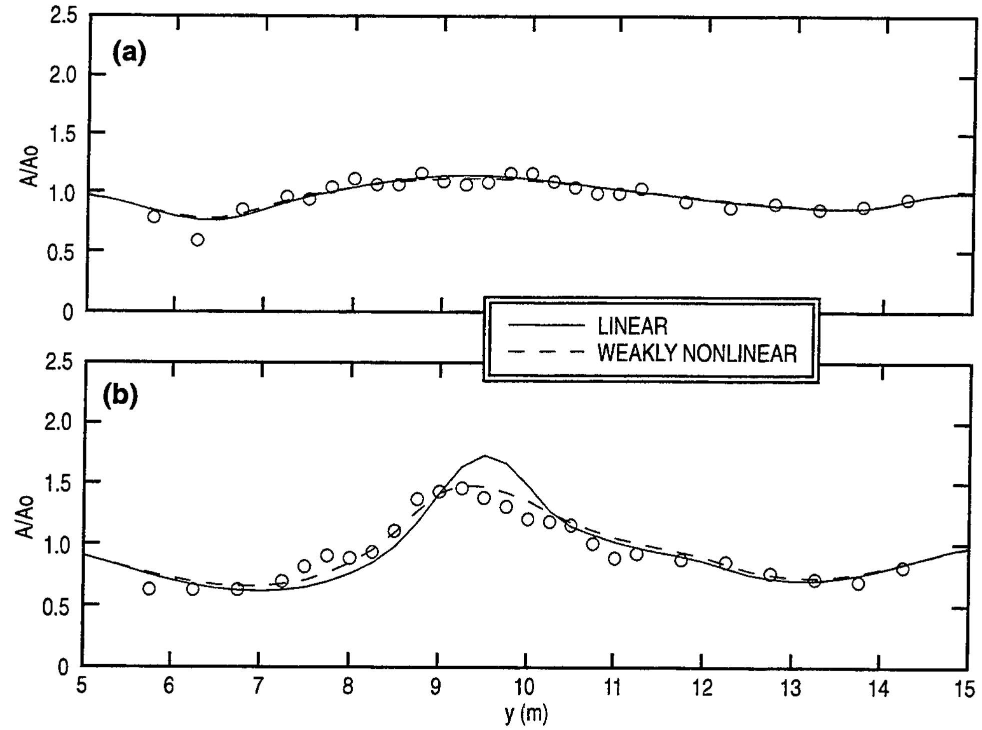

Fig. 16 — Wave height comparisons for (a) transect 1 and (b) transect 2, BBR experiment

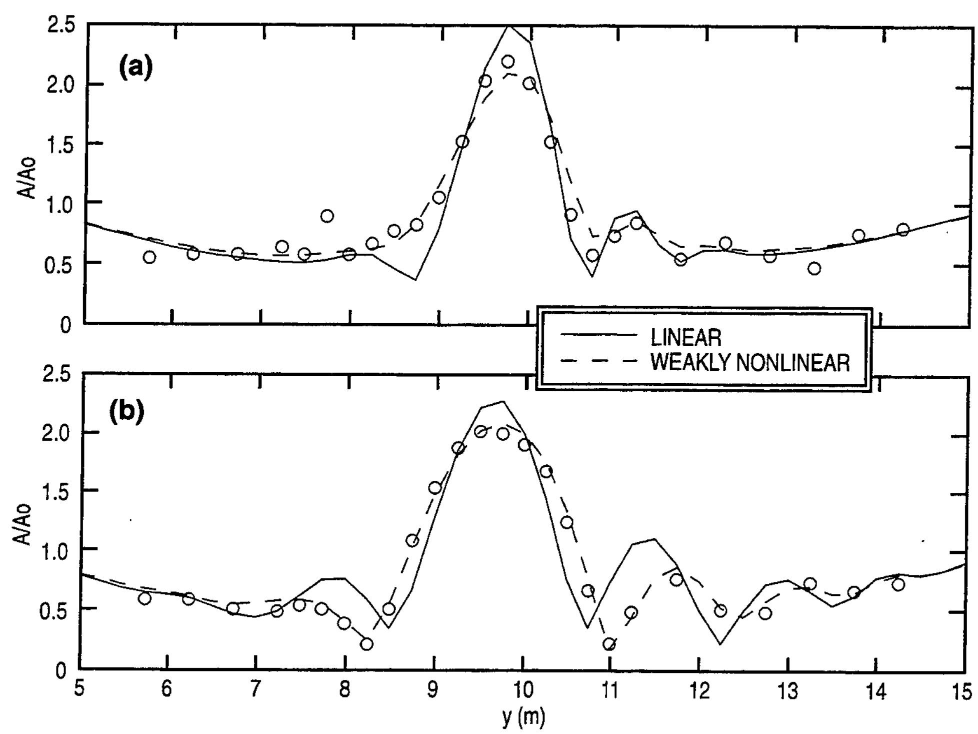

Fig. 17 — Wave height comparisons for (a) transect 3 and (b) transect 4, BBR experiment

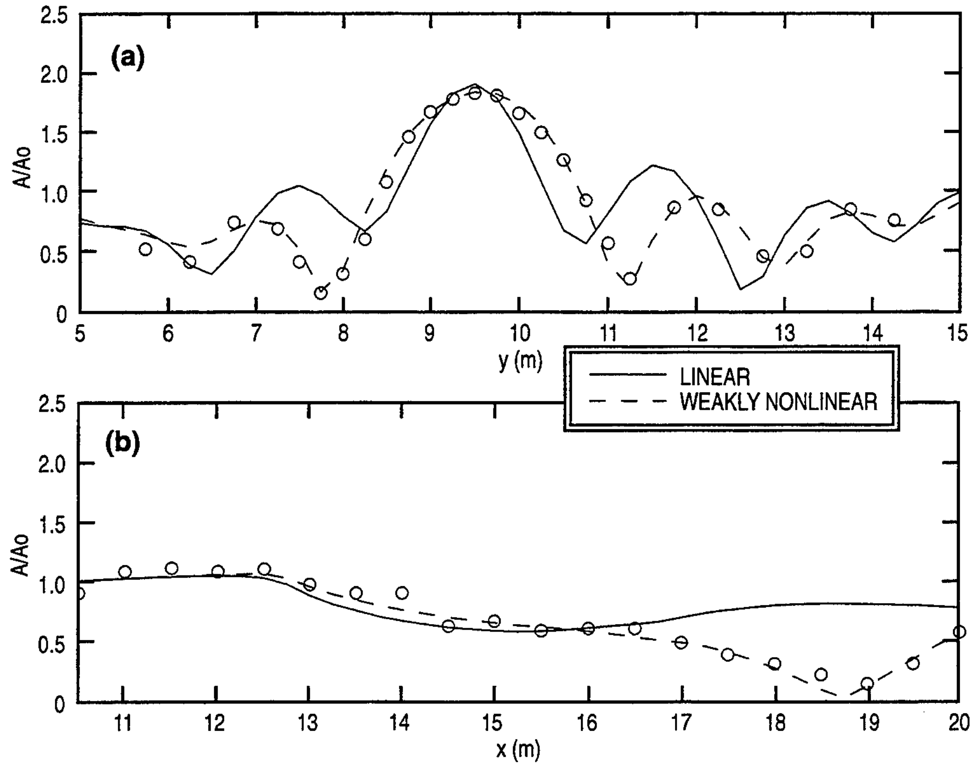

Fig. 18 — Wave height comparisons for (a) transect 5 and (b) transect 6, BBR experiment

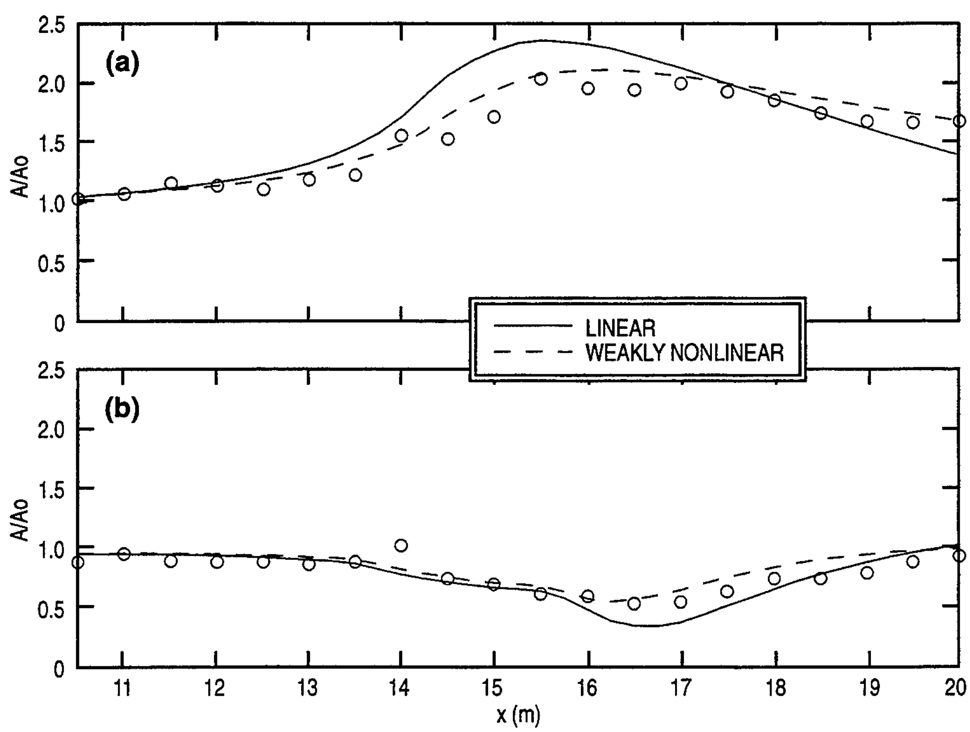

Fig. 19 — Wave height comparisons for (a) transect 7 and (b) transect 8, BBR experiment

2. Vincent and Briggs Shoal Experiment

a. Description of the Experiment

Additional experiments on wave propagation over a shoal for both monochromatic and directionally spread irregular waves were conducted by Vincent and Briggs (1989). The experiments were conducted in a 1.5-ft-deep, flat-bottom tank. The elliptic shoal has a shape similar to that of the BBR shoal. Since the experimental setup is different from the BBR shoal, this experiment provides another good test for REF/DIF1. The bottom contours and computational domain are illustrated in Fig. 20.

b. Model Setup and Results

Modeling parameters include:

Domain: 25 m $\times$ 30 m
Grid spacing: 0.125 m $\times$ 0.125 m
At boundary: x = 0, $H = 0.055$ m
Wave angle = 0°
Wave period = 1.3 s

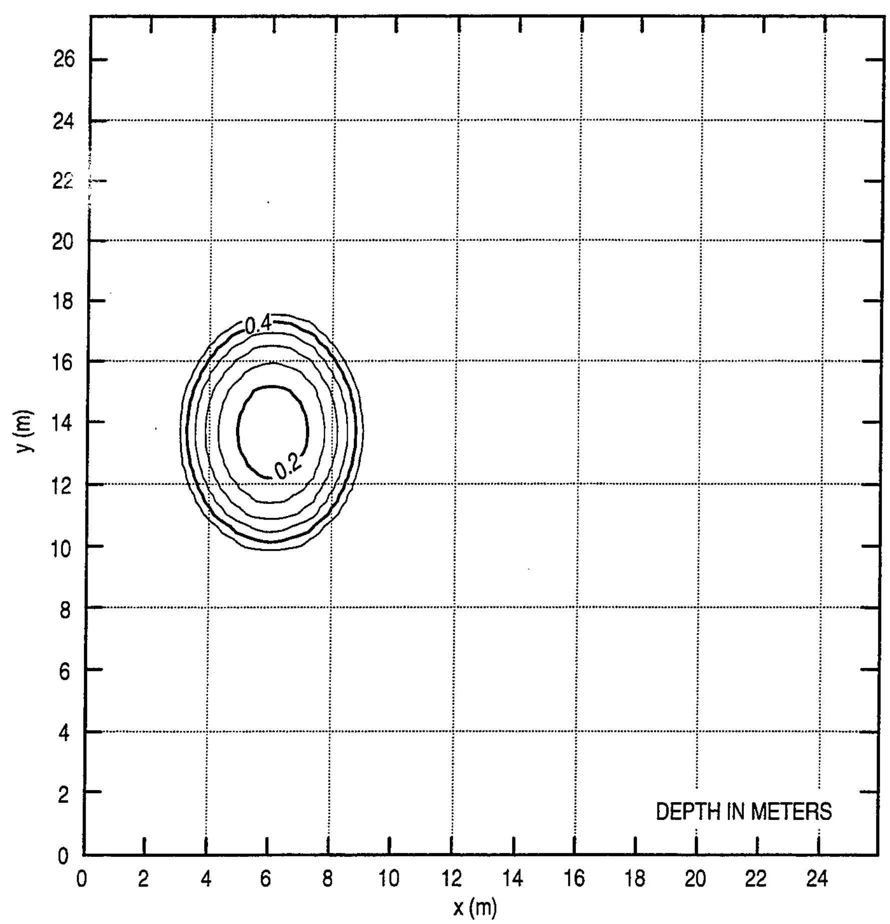

Fig. 20 — Bottom contours for the Vincent and Briggs shoaling experiment in a flat tank

Both measured and computed wave height contours are plotted in Fig. 21. The model again captures the strong convergence region behind the mound where wave height amplification exceeds 2.0. In general, REF/DIF1 matches the measurement very well. In Fig. 21b, linear dispersion is used, whereas nonlinear dispersion is used in Fig. 21c. As the wave shoals, it becomes more nonlinear and actually refracts less than linear waves do. This causes the focal point to move farther downwave than linear theory would predict, and explains why the location of maximum wave height amplification in the experimental picture are farther behind the shoal in the nonlinear case. It also explains why the nonlinear REF/DIF1 comparisons to the BBR experiment in the previous section fared better than the linear model comparisons.

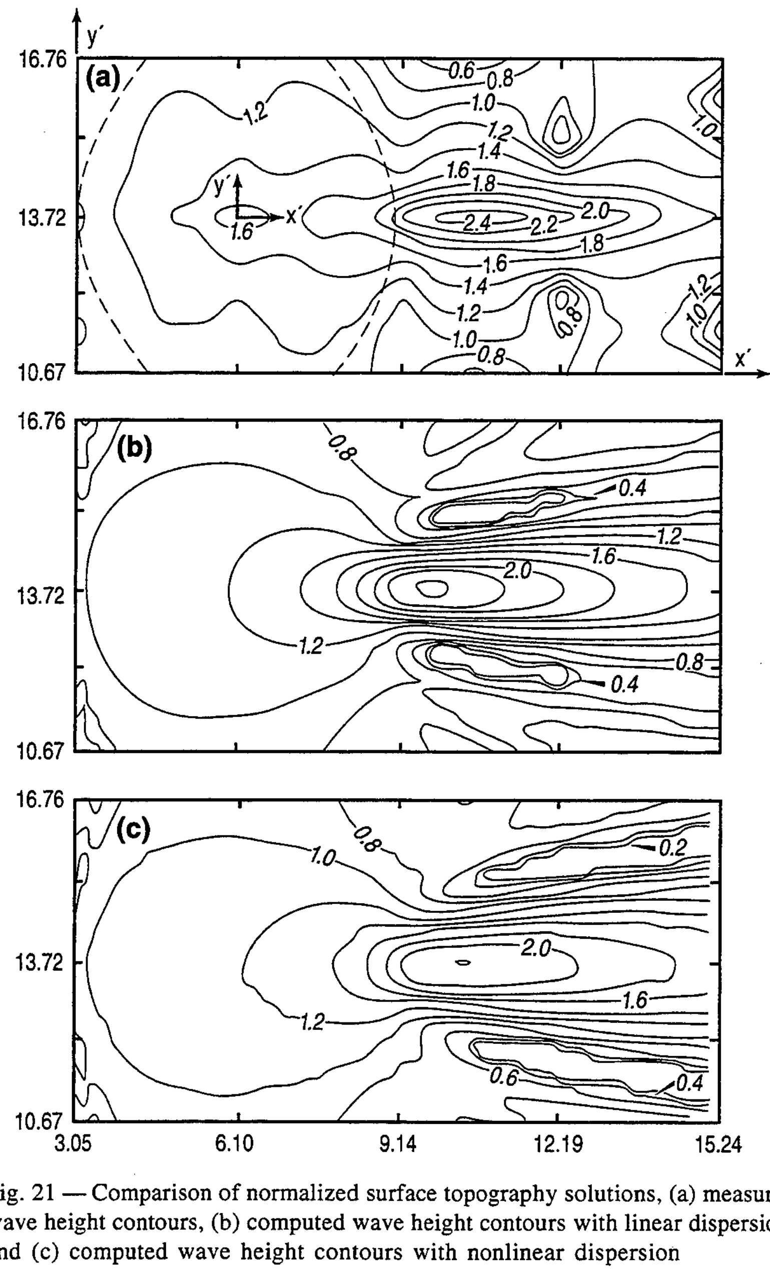

Fig. 21 — Comparison of normalized surface topography solutions, (a) measured wave height contours, (b) computed wave height contours with linear dispersion, and (c) computed wave height contours with nonlinear dispersion

C. Energy Decay Test

1. Energy Decay Model

The wave height decay mechanism was also checked because of depth-induced breaking implemented in the REF/DIF1 model. This mechanism reduces the wave height after breaking occurs. Examples of the effects of breaking have previously been shown in Figs. 1–12. The mechanism follows the theory of Dally et al. (1985) who proposed that the decay of energy flux in the surf zone is proportional to the excess of energy flux over a stable value. The relation can be expressed by the following

$$\frac{\partial}{\partial x}\left(EC_g\right) = -\frac{K}{h}\left[EC_g - \left(EC_g\right)_s\right], \tag{6}$$

where K is an empirical determined constant and $(EC_g)_s$ is the stable energy flux. An analytic solution for this energy flux decay exists for the cases of flat-bottom and planar bathymetry (Kirby and Dalrymple 1986a). Defining $\alpha = K/s$, where s is the beach slope, the wave height is related to the local water with the following two expressions

for $\alpha \neq \frac{5}{2}$,

$$\left(\frac{H}{H_b}\right)^2 = \left(\frac{h}{h_b}\right)^2 \left[(1-\Delta)\left(\frac{h}{h_b}\right)^{\alpha - 5/2} + \Delta\right], \tag{7}$$

where $\Delta = \dfrac{\alpha}{\alpha - \frac{5}{2}}\left(\dfrac{\gamma}{\kappa}\right)^2$; and for $\alpha = \frac{5}{2}$,

$$\left(\frac{H}{H_b}\right)^2 = \left(\frac{h}{h_b}\right)^2 \left[1 - \frac{5}{2}\left(\frac{\gamma}{\kappa}\right)^2 \ln\left(\frac{h}{h_b}\right)\right], \tag{8}$$

where $\kappa = \dfrac{H_b}{h_b}$ (at breaking).

2. Model Setup and Results

Other modeling parameters include:

Domain: 133 m $\times$ 110 m
Grid spacing: 1 m $\times$ 1 m
At boundary: x = 0, $H = 1$ m
Wave period = 5 s

Figure 22 shows the results of the comparisons for two values of bottom slope. The axis labels refer to wave height and water depth normalized by the values at breaking. It is clear the model approximates the analytical solution quite closely. It should be noted that this test only confirms

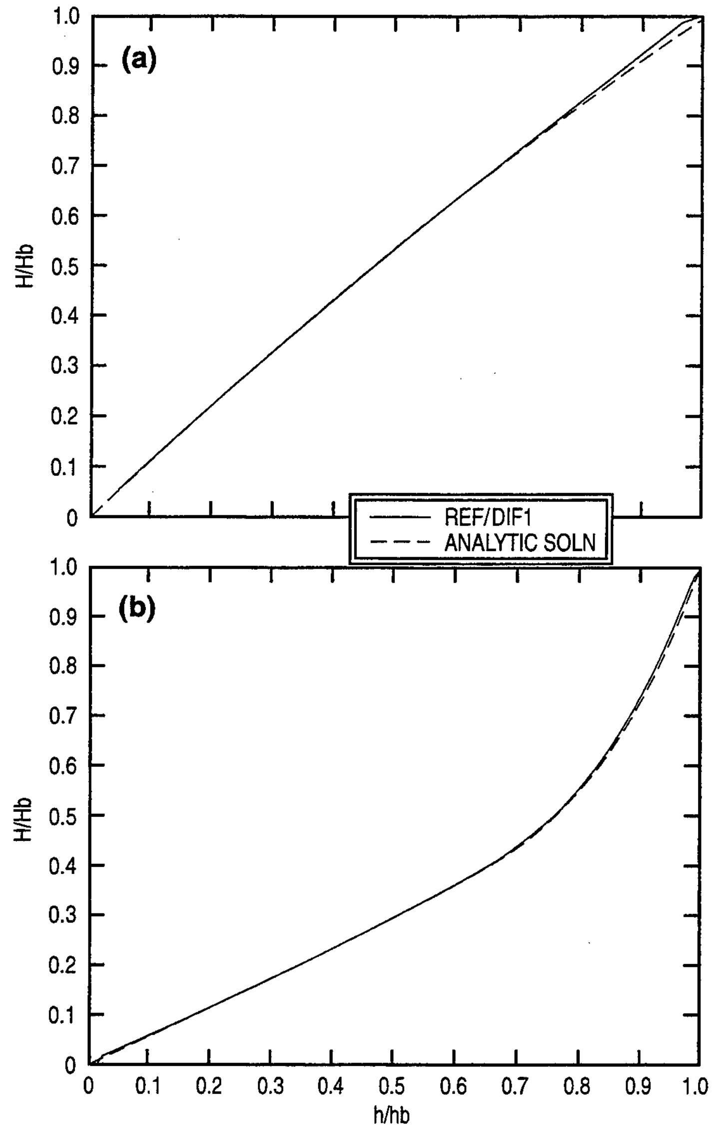

Fig. 22 — Dissipation test comparison, (a) slope = 0.05, $\alpha = 3$ and (b) slope = 0.015, $\alpha = 10$

the accuracy of the model computation of the implemented proposed breaking mechanism; it is not a "true" validation test for the breaking mechanism. The comparison modeling breaking wave and field is presented in Sec. II-E.

D. Wave-Current Interaction

1. Theoretical Solution

REF/DIF1 includes wave-current interaction computation as described by Kirby (1984). For test cases, the examples presented in Booij et al. (1988) were followed. The analytic solutions can be derived from the conservation of wave action outlined by Peregrine (1976).

2. Model Setup and Results

Two scenarios were tested to evaluate wave-current interaction modeling by REF/DIF1. In case 1, the waves and the current were moving in the same direction (the "following" scenario), whereas in case 2, waves and currents are heading in opposite directions (the "opposing" scenario). The wave model was run with a period of 5 s and a 0° approach angle. The offshore depth was 100 m.

Other modeling parameters include:

Domain: 1000 m $\times$ 4000 m
Grid spacing: 40 m $\times$ 40 m
At boundary: x = 0, $H = 1$ m
At boundary: x = 0, $U = 0$ m/s
At boundary: x = 1000, $U = 1$ m/s

In Fig. 23a, the spatial distribution of opposing currents is illustrated. The current varies linearly with distance from the wave origin. The comparison between computed and theoretical

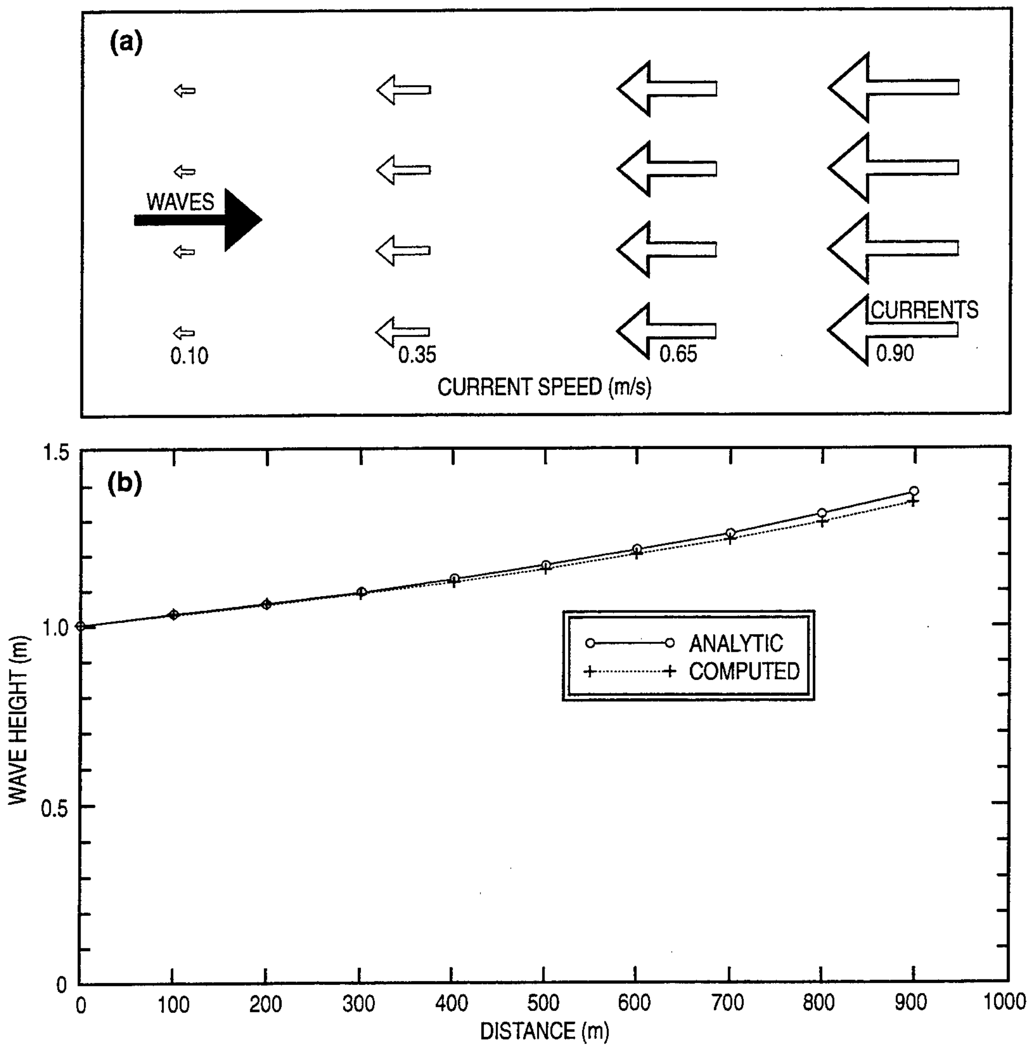

Fig. 23 — Wave-current interaction test, (a) opposing current distribution and (b) wave height comparison

results is presented in Fig. 23b. As expected, wave height increases with stronger opposing current. The computed result is slightly higher than that from the theory. The deviation increases as current velocity increases. In Fig. 24a, the pattern of the following current is illustrated. The comparison between computed and theoretical results is shown in Fig. 24b. In such a case, wave height is decreasing with increasing following current. Agreement between computed and theoretical results is very good.

E. Field Data Comparison

1. DELILAH Experiment

The DELILAH nearshore experiment was held at the Coastal Engineering Research Center (CERC) field research facility in Duck, NC, during October 1990. The DELILAH experiment was designed to investigate surf zone physics using a variety of techniques and instruments. Through the courtesy of the nearshore community, the data sets were recently made available. The data sets

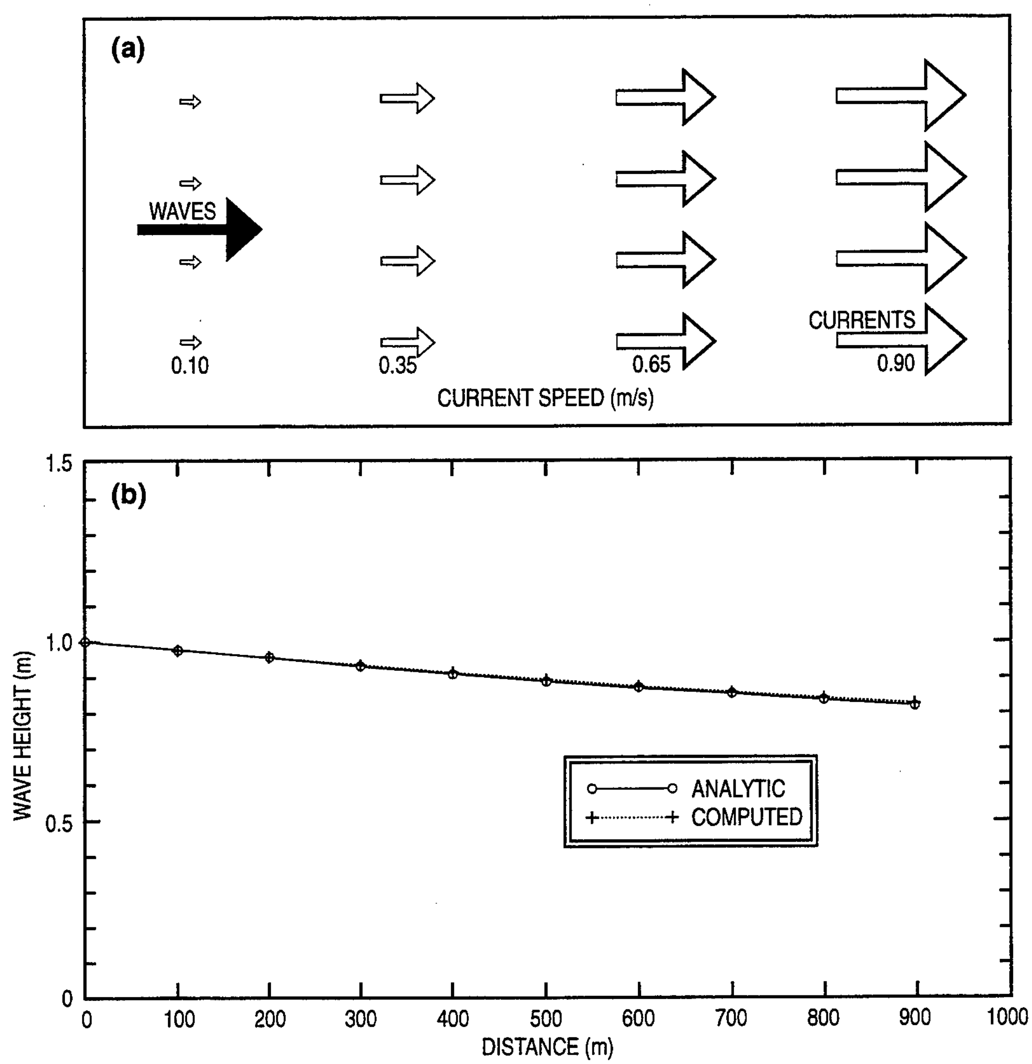

Fig. 24 — Wave-current interaction test, (a) following current distribution and (b) wave height comparison

consist of high-quality bathymetry, wave, surf, and longshore current data for a period of 3 wks. The gauge arrangements and general map of Duck are presented in Fig. 25.

2. Model Setup and Results

The model domain and bathymetry contours at Duck are plotted on Fig. 26.

Other modeling parameters include:

Domain: 1695 m × 1588 m
Grid spacing: 13.45 m × 13.45 m

The model was initiated at a depth of 14 m using the Sources of Ambient MicroSeismic Oceanic Noise (SAMSON) gauge data. The wave condition (hour 1600 at 7 Oct) is a swell with a significant wave height of 0.52 m, a period of 9.71 s, coming from the south at a direction of 44°. The directional wave data are presented in Fig. 27. In REF/DIF1, the wave condition was set to a single swell component. It should be noted that it is often necessary to run REF/DIF1 at finer frequency and angular bandwidths over an area with complex bathymetry. For example, 0.002 Hz frequency bandwidth and 1° angular bandwidth are required over the Southern California Bight (O'Reilly and Guza 1993). In REF/DIF-S, the directional spectra were divided into 10 frequencies and 20 angular bands as the input condition. The comparison between REF/DIF1 and REF/DIF-S with field data are plotted in Fig. 28. The symbol (*) represents nearshore gauge data and the dashed line outlines the bottom profile. Both models predict the wave distribution reasonably well.

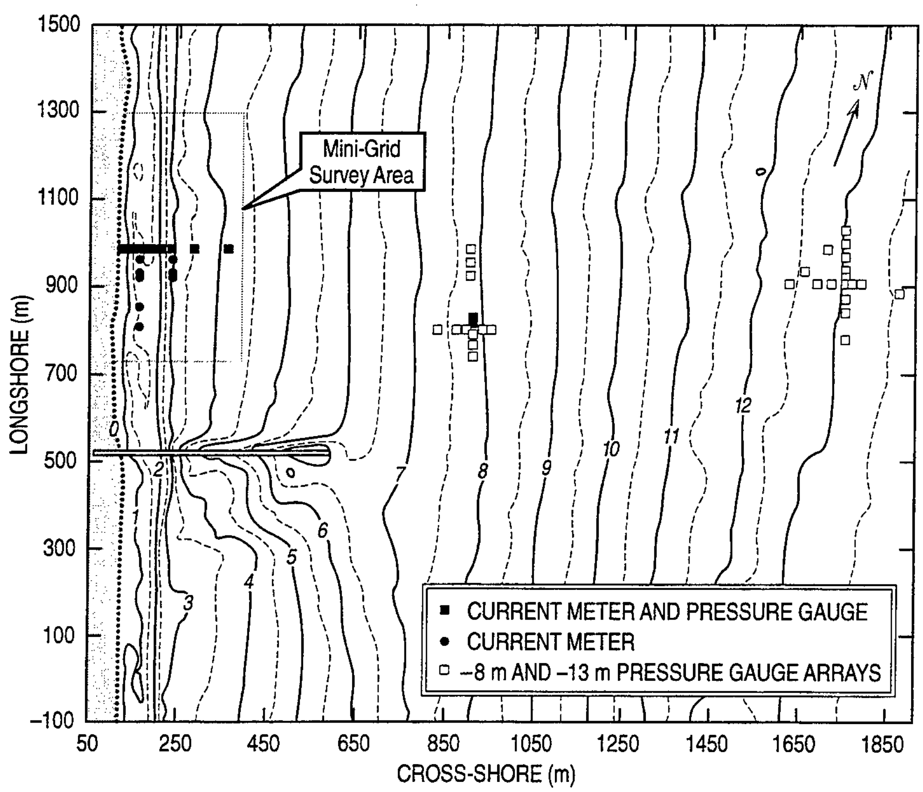

Fig. 25 — Deep sled survey contour map with the minigrid area outlined (from DELILAH Investigators Report)

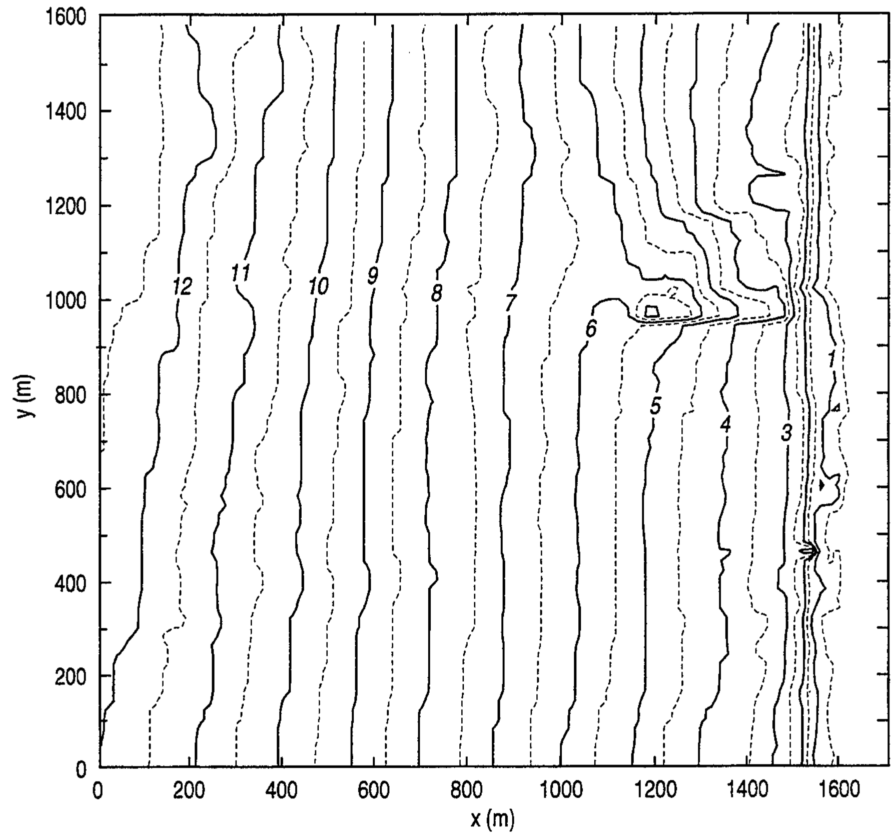

Fig. 26 — REF/DIF1 model bathymetry for Duck, NC

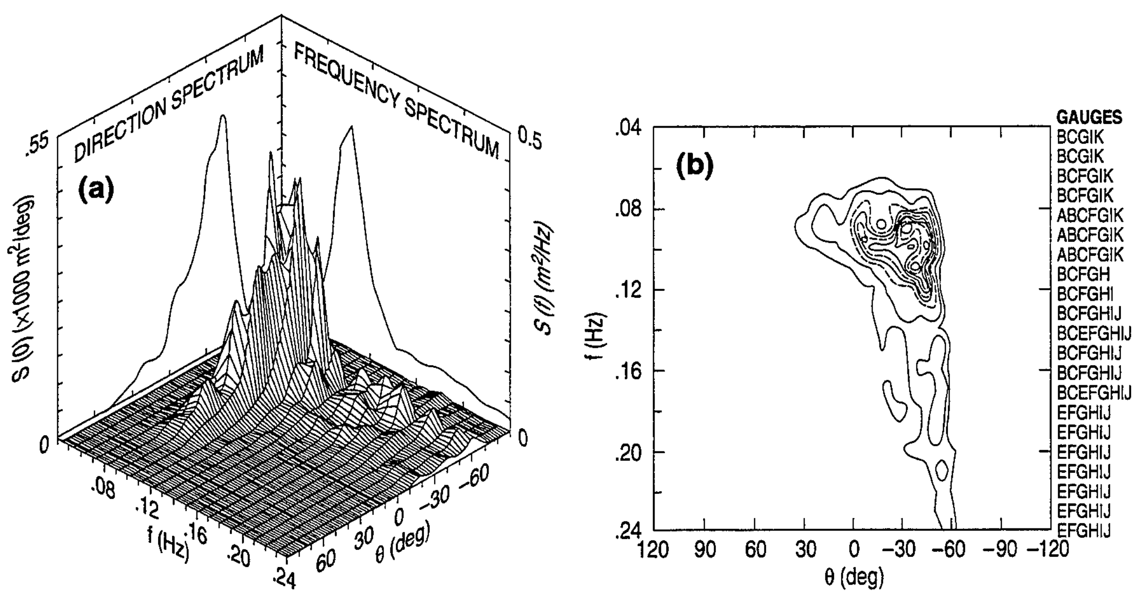

Fig. 27 — Sample directional wave spectrum (a) SAMSON linear array frequency-direction spectrum, date: 07 Oct 90 at 1600 EST for 136.53 min with 160 dof $H_{m0} = 0.52$ m, $f_p = 0.103$ Hz, $T_p = 9.71$ s, $\theta_p = -44°$; depths: min =12.63 m, mean = 12.77 m, max =12.99 m at gauge 3011 and (b) contours at 5% and then tenths of maximum $S(f,\theta)$ (from C. Long, CERC)

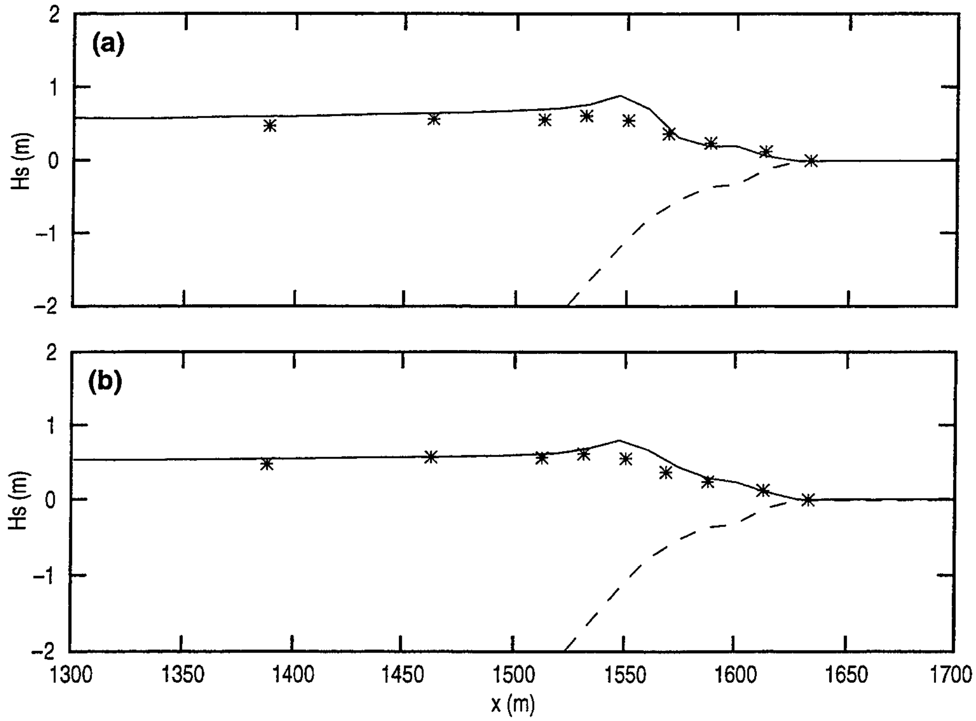

Fig. 28 — (a) REF/DIF1–DELILAH experiment, 10 Oct 90, 1600 EST and (b) REF/DIF-S output

The REF/DIF-S model provides a smoother answer and a better maximum wave height fit in the surf zone, as is expected from a spectral model where waves propagate simultaneously in the model domain. A detailed model comparison with DELILAH data are documented in another report (Rogers et al. 1997).

III. SUMMARY AND CONCLUSIONS

A systematic set of tests has been conducted to evaluate the REF/DIF1 coastal wave model. The tests evaluated shoaling and refraction, combined refraction and diffraction, energy decay, and wave-current interaction properties of the model. The model results were compared to analytic solutions from linear wave theory, laboratory, and field data. REF/DIF1 was found to perform adequately in all tests. REF/DIF1 is now being submitted to the Oceanographic and Atmospheric Master Library (OAML).

REF/DIF1 is also being integrated into the Navy-Standard surf model (NSSM). It provides directional wave input to the surf zone model. In most cases, REF/DIF1 will be run many times at different frequencies and directions to simulate the wave condition that can consist of a combination of swells and directional sea. The results will then be linearly combined to feed the surf zone model. Outside the surf zone, where wave-wave interaction is weak, the superposition approximation is adequate. Inside the surf zone, REF/DIF-S has been shown to perform better than REF/DIF1. In NSSM, the wave height transformation computation in the surf zone uses the same breaking formulation (Thornton and Guza 1983, 1986) as REF/DIF-S. Consequently, similar wave height transformations are to be expected. Therefore, there is no immediate need to include REF/DIF-S in NSSM.

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